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PROJECT COST ESTIMATING

R. L. Petruschell

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R. L. Petruschell*

The RAND Corporation, Santa Monica, California

INTRODUCTION

Cost estimating is all too frequently thought of as a necessary but dull and uninspiring task better performed by persons who are either incapable of, or uninterested in, wrestling with the important and exciting issues of the day. Even with the current concern for the economic implications of choice, cost estimating is only beginning to be accorded its rightful place in the decisionmaking process. The reasons for this are many, but the most significant is probably just a general lack of awareness of the potential benefits that are to be realized. One place where cost estimating has, in recent years, been allowed to play its proper role is in military long-range planning, and the rewards have indeed been great. The general philosophy of the military planner and the concepts and methods of the cost estimator that have permitted this to happen are discussed in the first part of this paper. In the second part, an example of a cost analysis in support of a military planning problem is presented. The example points up the fact that cost estimating can be an intellectually stimulating activity worthy of the application of the best analytical skills available; and second, that it can provide useful answers to difficult and important questions even when uncertainty is great and quantification is difficult. Even though the discussion in this paper is based on a military long-range planning application, the concepts, methods and techniques that have made success possible there, have much more general implications. Believing this, the author hopes that this paper will serve to further

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the awareness of many, and stimulate some, to actively seek out the important benefits to be derived from a less traditional approach to cost estimating.

PROJECT COST ESTIMATING FOR MILITARY PLANNING

Weapon and support systems, the building blocks of the military planner, require long lead times, and the commitment of substantial quantities of national resources, for their acquisition. The long lead times force the planner to focus his activities on a distant time horizon and, at the same time, permit him to consider a wide range of alternatives. Because the resources available to him are limited, the planner may not do all that seems desirable and must therefore make choices from among the alternatives available. It is in assisting him to make efficient use of the resources that the cost estimator plays his role.

The efficient allocation of limited resources among competing objectives is the problem typically addressed by the economist. His concern is with the requirements for manpower, for facilities, and for the raw materials to achieve an objective, as well as with the monetary implications. In supporting the long-range planner the cost estimator takes much the same view. The lack of descriptive detail, and the uncertainty typically associated with the distant time horizon of the military planner, make it impossible to use conventional cost estimating methods to get at the resource implications of the alternatives. The process is instead an "analytical" one relying heavily on the use of highly generalized estimating relationships based on past experience. To stress these two points, the terms "resource" and "analysis" are frequently substituted for "cost" and "estimate."

Even within the context of military planning, resource analysis may be applied to a broad spectrum of problems and each has its own special impact on the nature of the methods used.

At one end of the spectrum the problem is to illuminate the resource implications of alternate weapon design specifications and system operating characteristics. Such analyses necessitate "in-depth" consideration of a single system and are most frequently used to help put together an initial system description. This technique is called "Intra-System" resource analysis.

After a preferred configuration has been identified, the question logically turns to whether the given system is preferred to a number of others. Here resource analysis is used to provide information about the resource implications of each of the alternatives and is referred to as "Inter-System" resource analysis. Rather than providing an in-depth analysis of a single system, inter-system analysis concentrates on isolating those features of each of the alternative systems that cause the resource requirements to differ.

It is infrequent that a military planner has as simple a choice as between one weapon system and another. The more typical case requires choosing some number of each, and the question is, then, how many? Here, the resource analysis problem is to determine the aggregate resource implications of alternative mixes or groups of weapon systems and is called "Total-Force" resource analysis. In this form of analysis, the way in which the various systems interact with each other as they compete for available resources is stressed. The objective is to show the time-phased, net resource requirements resulting from the total force rather than the cost of a single system.

While the form of the analysis influences the specific methods used, the basic concepts of resource analysis, largely determined by the characteristics of long-range planning, are common to all.

Probably the single most influential characteristic of military long-range planning, from the point of view of the resource analyst, is the time horizon, which extends five, ten, or even fifteen years into the future. His sights on the future. the planner is freed from many of the constraining influences of the present and consequently is able to consider a wide range of alternative ways of accomplishing his objectives. However, the price he pays for this freedom is measured in terms of the difficulty he has in specifying anything definitively, and the uncertainty with which he must live.

In the last analysis, the number and kind of alternatives the long-range planner considers are limited only by his imagination. Alternative weapon designs, alternative ways of operating a given system, alternative systems, and alternative forces or mixes of systems, are indicative of the classes of alternatives open to him. With the emphasis on making a preliminary selection of the more promising, from among the many possible alternatives, it is unlikely that more than the major features of each will be identified. Proposed aircraft are typically described by stating their gross weight, speed, number and type of engines, payload, and little else. Differentiation between alternative weapon systems is likely to be in terms of the distinguishing characteristics of the major hardware items and suggested activity rates alone. Given all of this, the certainty with which any one of the proposed alternatives can be expected to perform as stated is dubious at best. This is the environment in which the essential precepts of military cost analysis have been formulated.

CONCEPTS AND METHODS OF MILITARY COST ANALYSIS*

One of the most fundamental concepts of military cost analysis is that cost estimates are never made for their own sake alone. Such an estimate is but one of many inputs into the planner's decision process and has meaning only when viewed together with appropriate measures of effectiveness or utility. Weapon systems, whose utility can be measured, have become the building blocks of the military planner and consequently the focus for military cost analysis.

Even though the major hardware components of a weapon system are typically the most costly, requirements for related resources, such as highly trained personnel or exotic materials when estimated to be in short supply, may dictate the planner's choice. For this reason <u>all</u> of the resources necessary to create, install and maintain the complete weapon system are germane. The concept of <u>total</u> weapon system cost reflects this desire for comprehensiveness.

Resources required throughout the entire life of the weapon system must also be considered, including those required for research and development, for system acquisition, and for system operation until

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*While this discussion of military cost analysis is relevant to all branches of the military, much of the language and the choice of illustrative material reflects the long association of the author with the specific problems of the U.S. Air Force.

phase-out. This is the concept of total life-cycle, which states that all of the resources necessary to fulfill each of these functions shall be estimated and separately identified. Because resources committed to each of these phases in the life of a system bear a different relationship to time and to the number of units of the weapon system procured, displaying them separately facilitates greatly the planner's evaluation. Research and development costs are relatively independent of both time and the number of units eventually procured. System acquisition costs are also independent of time, but directly related to the number of units procured; while operating costs are related to the number of units procured, and to the anticipated life of the system. This identification facilitates distinguishing between those systems with relatively different requirements for one-time and recurring costs, and provides the planner with the ability to approximate the cost of varying the force size and the number of years of operation.

A planner can always expect to introduce a future weapon system into an existing military force and must understand that the weapon selected will be only an augmentation to that force. Consequently, it is the concept of net additional, or incremental, resource requirements associated with making these augmentations that is relevant. Sunk costs and resources on hand are of interest only in that, if available, they may help to reduce the incremental costs.

As it cannot be expected that the total quantity of resources available will be radically different from one time period to another, scheduling the introduction of new systems and the phasing out of old ones so that relatively even demands for resources are created becomes a primary job of the planner. To allow him to do this, estimates of time-phased costs must be provided as well.

Estimating with absolute accuracy, under conditions of uncertainty, is recognized as being out of the question. Therefore, the analyst concentrates on achieving relative accuracy and treating each alternative consistently.

The methods used to make cost estimates are many and varied. There are instances when expert opinions and informed judgment provide the only basis for an estimate, and others where more formal methods are used. One way of identifying the more formal methods is to divide them into three categories: statistical method , engineering methods, and accounting methods.

The statistical method is to use multiple correlation and regression analysis to find and describe functional relationships between resource requirements and specific elements of system description, such as weight, speed, activity rates and number of personnel. Historical data, describing activities assumed to be consistent with those projected for the future, are the basic ingredients of this method. Though not necessarily so, this method is usually applied at a relatively high level of aggregation, and to estimating problems involving very advanced weapon systems.

The essence of the engineering method is to break the system, or item of hardware for which the resource requirements are to be estimated, down into lower level components such that meaningful conjectures about the resource implications of each can be made. Statistical methods are frequently applied at this lower level of detail, and the results are then combined with the estimates of the resources required to integrate the components and the total is obtained. One of the most useful properties of this method is that it helps separate those parts of the problem that require novel treatment from those that can be dealt with conventionally. A disadvantage is that it frequently leads to underestimating, because inadequate allowance is made for the cost of integration. When it is necessary that the engineering method be used, the statistical method is often also applied at a more aggregate level of detail to insure against underestimating.

The accounting method relies on the fact that certain factors, or estimating relationships, are inherent in the books of account, financial or otherwise. Overhead rates, labor rates and material consumption rates are examples. Conceptually, the method is simple, but does usually require that estimates be made at a relatively lower level of detail than is generally practical. Further, when using the accounting method, extreme caution must be exercised to insure that misleading impressions, resulting from using the relationships out of context, are not conveyed.

As is obvious, each of these methods has both advantages and disadvantages, but, typically, all resource estimates prepared use all of them in varying proportions. How much, depends on many factors, including: the time available to make the estimate, the preciseness required, the type of analysis contemplated, the availability of descriptive information, the form and availability of relevant historical data, and the extent to which the subject of the estimate is a departure from past experience. In the last analysis, the selection depends on the experience and the preference of the individual analyst.

Cost effectiveness analysis, cost-utility analysis, cost benefit analysis, and systems analysis, each suggest methods for making comparisons considering both cost and effectiveness. These analyses take on many and varied forms, some more satisfactory than others, and each has its proponents. The systems analysts have found two analytical forms to be preferred. The first is called "fixed budget" analysis, and the second "fixed effectiveness" analysis. Fixed budget analysis assumes a predetermined budget and uses it to procure as many units as possible of each of the weapon systems to be compared. The effectiveness of each system, based on the number procured, is estimated and the system providing the maximum effectiveness for the stipulated budget is preferred. The fixed effectiveness analysis starts by assuming a level of effectiveness and proceeds to examine the cost of achieving it, using each of the alternative systems. The least costly alternative is preferred. One shortcoming of these approaches is that by arbitrarily selecting either a budget or a level of effectiveness an inefficient use of marginal resources may be suggested. Only when the relationship between effectiveness and cost is linear throughout its entire range will this danger not exist. However, making similar comparisons under different assumptions about levels of resources or effectiveness insures against this without greatly complicating the analysis.

Cost-effectiveness ratios are frequently used to make comparisons because of their conciseness, their non-dimensionality, and their ability to fit neatly into relatively simple analytical models. With all of these advantages, however, they should be used with extreme caution. Most people have difficulty enough understanding a cost-effectiveness comparison when either one of the two dimensions is held constant. When both are allowed to vary si 'taneously, as is the case with any ratio, the difficulties are compounded.

Crucial to a choice among alternative weapon systems is the question of relative availability time-wise. Consider the case where an otherwise preferred alternative is not available for some number of years. If the job must be done sooner, another alternative must be chosen. Further, having made the choice, the relative merits of the two alternatives may well look different. This point is particularly important because in most analyses one of the alternatives is a continuation of an existing weapon system and another is a system that won't be available for ten years.

A COST SENSITIVITY ANALYSIS OF AN ANTI-SUBMARINE-LAUNCHED BALLISTIC MISSILE SYSTEM: AN EXAMPLE

Cost sensitivity analysis is the cost analyst's most useful tool for dealing with uncertainty. The primary objective is to provide a system designer or a planner with insights into the way system costs are influenced by changes in specifications. Knowledge that the costs of a system are either sensitive or insensitive to the value of a particular parameter about which there is uncertainty can help to guide the design process by focusing attention on areas with potentially high pay-offs. The product of a cost sensitivity analysis is, therefore, a set of relationships, graphic or otherwise, that describes the way resource requirements react to changes in assumptions and input values.

Cost sensitivity analysis is most beneficial when it is treated as an integral part of the system design and planning process. The system designer specifies a system. The cost analyst determines the resource implications of the initial descriptions. The system designer reacts by changing his specifications and in this way the process continues. At no time is the study really completed. As one iteration is finished, questions leading to another are raised, and a systematic and orderly approach to acquiring insights is achieved.

With the emphasis on describing relationships, absolute values are of secondary interest. Their main use is for ranking the alternatives considered. The large number of variables and the complexity of the interrelationships typically involved require the sensitivity analysis to be conducted on an incremental learn-as-you-go basis. Anything more ambitious typically leads to complete confusion. Just how all of this works will be demonstrated as we proceed to investigate some of the resource implications of a proposed system for defending the United States against a submarine-launched ballistic missile attack. It will be obvious, as the example unfolds, that as many questions are raised as are answered. This is as it should be; for asking the right question is often the most difficult and important part of analysis.

There are two logically separate and distinct operations required to prepare an estimate of the cost of a system: estimating the requirements for physical resources and translating the resource estimates into statements of monetary requirements. Frequently the two are performed simultaneously and thus lose their individual identities. This was not the case, however, in the study that will be described. In fact, the most interesting analytical problems encountered involved resource considerations primarily. Estimating the monetary requirements, while not a trivial problem, was handled in a relatively straightforward fashion and consequently is not given extensive treatment in this paper.

Defending the United States against an attack from a submarine-launched ballistic missile, using manned aircraft armed with anti-missile missiles and carrying infra-red detection equipment or radar, is the major mission of the system analyzed.* More specifically, it was assumed that an aircraft appropriately equipped and on patrol over the ocean, would be able to detect the launching of a ballistic missile. Having detected the launch, the missile's trajectory could be calculated using an on-board computer, and an interceptor missile could be

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*This example has also been used in P-3097, Cost Sensitivity Analysis, A. J. Tenzer, March 1965, and as Chapter VIII of the book, Systems Analysis for Policy Planning, edited by E. S. Quade and W. Boucher, The RAND Corporation. To be published.

launched from the aircraft such that an intercept would be made prior to the point where the submarine-launched missile entered the ballistic phase of its flight path. An alternate scheme, imposing less stringent requirements on the interceptor missile and associated computer, was also suggested. This was based on allowing the intercept to be made after burnout and thereby increasing the time available. A third variation was predicated on the fact that detecting a launch also provided information about the location of the submarine. This being the case, an anti-submarine missile having the potential of destroying the submarine and all remaining missiles could be launched as well. A mixed system resulted.

Estimates of the lead times required for obtaining a decision to go ahead, to accomplish the necessary research and development, and to produce and install the equipment indicated that none of the proposed systems could be fully operational in less than ten years, thus fixing the planning time horizon.

A token operational plan was also suggested. It was assumed that the aircraft would be deployed around the perimeter of the country on air bases already in existence. It was recognized that the feasibility of this would depend on the total number of aircraft involved and on the availability of air bases; therefore, verifying this was made a specific objective of the analysis. Having no indication that one part of the country would be more vulnerable to attack than another, it was decided that a uniform coverage of the entire perimeter would be necessary and alternate ways of accomplishing this were suggested. One required maintaining enough aircraft continuously airborne in specified locations to cover the entire area at all times. Another, assumed to be less expensive, required keeping most of the aircraft on the ground to be launched only when an alert was required. Still other variations, including providing complete coverage on a randomly selected basis, were considered and analyzed. However, most of the analytical work described in this paper is based on providing continuous and complete airborne coverage.

Various flight plans for the patrol aircraft were considered. One, as shown in Fig. 1, was to have the aircraft take off from its

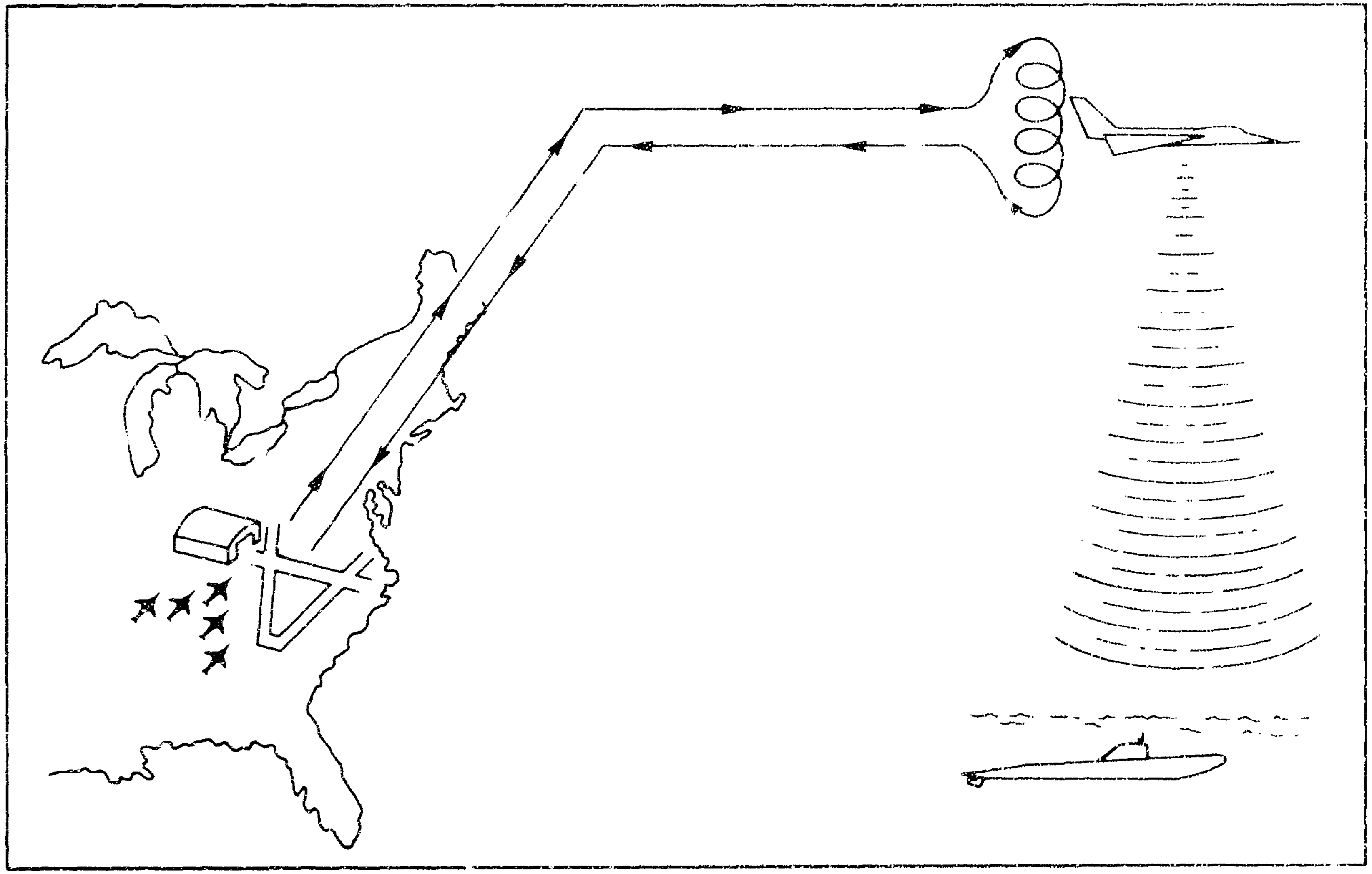

Fig. 1—Typical flight plan

base, fly to the specified patrol area, and remain on patrol until it has only enough fuel remaining to return to its base. Continuous coverage would be provided by scheduling a second aircraft to arrive on station as the first departs. Another possibility suggested was to fly a number of aircraft spaced at intervals around a closed course such that complete and continuous coverage of a specified area would be achieved. Other variations were considered as well, but these two received most of the attention.

Anticipating that the cost of the system would be sensitive to the total number of aircraft required, the size of the area to be patrolled and the contribution of each aircraft became key considerations. Assuming that the entire perimeter of the country had to be protected, the area became a direct function of the necessary off-shore distance, which was entirely dependent on predictions of the range of the enemy missiles. As such predictions were extremely uncertain, off-shore distance was treated as a variable in the cost sensitivity analysis. The contribution of an individual aircraft would be largely determined by the range of the airborne detection equipment and the speed of the interceptor missile. As neither of these items had yet undergone preliminary design, their characteristics were also uncertain and treated as variables.

The choice of an aircraft for the mission seemed obvious. All that appeared to be required was a relatively unsophisticated aircraft capable of keeping a large payload airborne for extended periods of time. Attention focused on transport aircraft in general, and on the KC-135 strategic tanker in particular. This aircraft not only had the desired characteristics, but was scheduled for phase-out at about the same time these requirements would be generated, thus making it available, and a free resource. For these reasons it appeared to be too good a possibility to pass up. Fortunately, the cost analyst took it upon himself to examine some other possibilities as well, and the results were among the more important contributions of the cost sensitivity analysis.*

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*Considerably more attention than has been indicated was paid to many other elements of the system. This was particularly true of the specifications of the interceptor missile and related airborne equipment. However, as those details are not essential to this presentation they have been omitted.

The above description is quite typical and, if anything, suggests the availability of more information than is usually provided. It also reflects many of the questions confronting the planner whose main concern is with either discarding the proposed system completely, or with selecting that variant that seems, within the resource constraints, to promise the highest probability of success. How the cost analyst, using cost sensitivity analysis, can help him to make the necessary decisions will be illustrated.

The cost analyst worked closely with the system designer to formulate the preliminary description of the system and during that time gained the impressions that guided his structuring of an analytical model. Any model, to be useful, must abstract the complications of reality. Those elements about which information is sought must be highlighted, while others are played down. In that respect, the structuring of the model largely determines the informational output of the analysis, and therefore places significant demands on the experience, the judgment, and the technical skill of the analyst.

As the system for providing continuous coverage from a fixed orbit point was conceptually the simplest, and was sufficiently representative of the suggested variations, it was selected for modeling. Treating each of the individual air bases that might eventually be required was also considered an unnecessary sophistication, and the concept of using a single generalized or typical air base was adopted.

The notion of a sortie-cycle, identifying all of the time spent by a representative aircraft performing the functions required by the mission, provided the underlying structure for the resource model. This cycle, shown schematically in Fig. 2, begins with the aircraft at the end of the runway awaiting take-off, and ends with the same aircraft once more in the same position. The individual segments of the cycle indicate those operations, each time-consuming, that are essential to the accomplishment of the mission. Separating the airborne and the ground activities, as indicated in Fig. 2, makes the utility of the sortie-cycle apparent and suggests some interesting analytical possibilities. The proportion of the time that each aircraft is airborne, and effective on station, provides a direct indication of the total

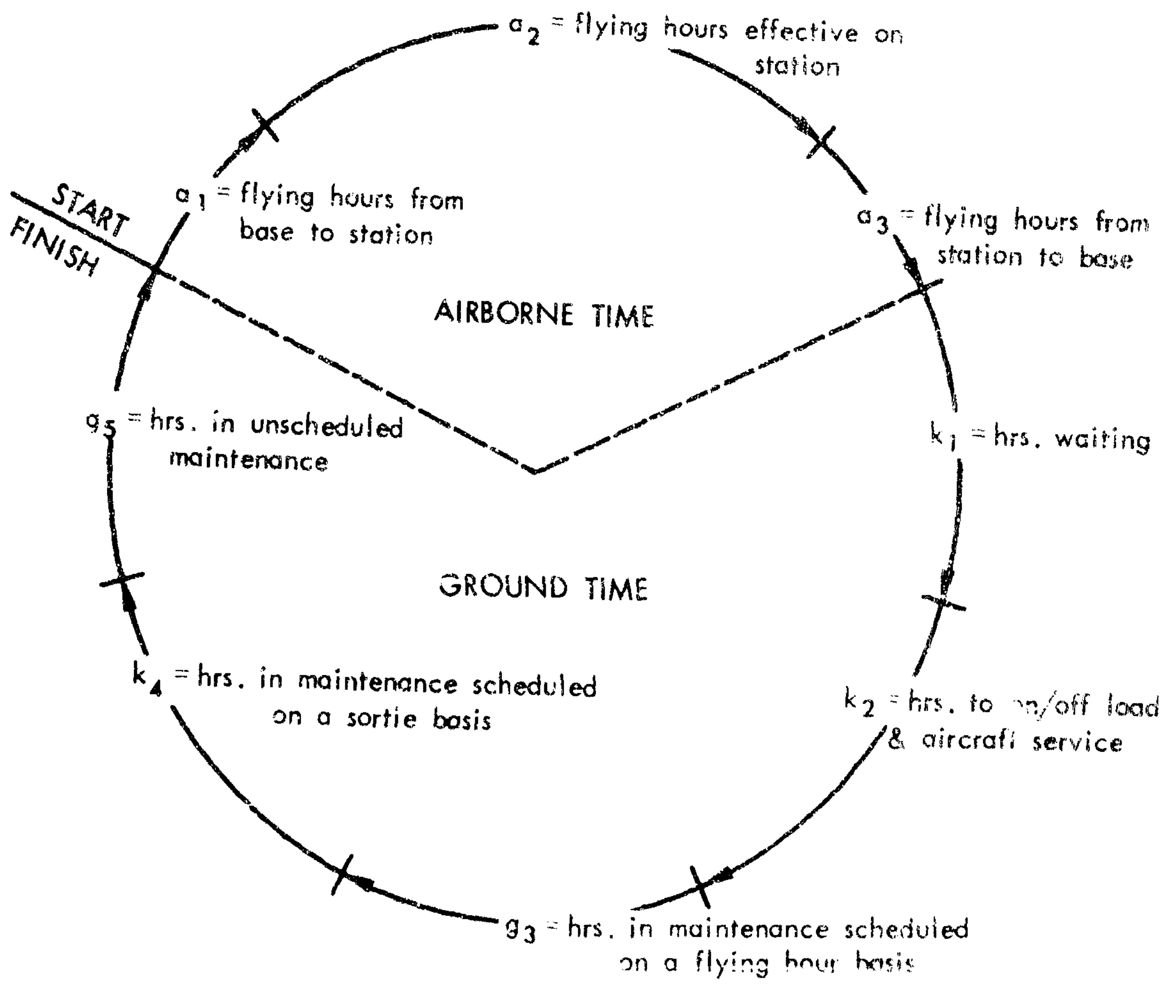

Fig. 2—The sortie-cycle

number of aircraft required to perform the mission. For example, if ten aircraft were required on station continuously and each aircraft spent one-third of its time there, a requirement for a total of 30 aircraft would exist. Alternately, if each aircraft spent half of its time on station, the requirement would be for 20. This suggests that a major concern of the analysis should be with those elements of the system that influence this proportion. Deployment (which influences the time spent going and coming), aircraft endurance (which governs the total time spent in the air), the number of shifts during which maintenance is performed (which affects the time spent on the ground), and the overall scheduling of the activities, are all possible candidates.

Obviously, some of the activities included in the sortie-cycle are interrelated, as are airborne time and maintenance scheduled on the basis of flying hours. Structuring the model, therefore, requires that these interrelationships be made explicit. In somewhat simplified form this was accomplished as follows. Using the symbols indicated in Fig. 2, the sortie-cycle was defined, mathematically, as the sum of its individual parts.

$$S = a_1 + a_2 + a_3 + k_1 + k_2 + g_3 + k_4 + g_5 \qquad (1)$$

where S = total cycle time

a_1 = flying time from base to station

a_2 = flying time effective on station

a_3 = flying time from station to base

k_1 = time waiting (an indication of inefficient scheduling)

k_2 = time required to on/off-load and service the aircraft

g_3 = time spent performing maintenance scheduled on the basis of accumulated flying hours

k_4 = time spent performing maintenance scheduled for accomplishment each sortie and independent of accumulated flying hours

g_5 = time spent performing unscheduled maintenance.

Including the maintenance which needs to be carried out after more flying hours than are generated during a single sortie, g_3, required a slight departure from reality. When, for example, an inspection was required after each 600 flying hours and each sortie contributed 60, one-tenth of the total time necessary to perform the inspection was identified to each sortie. Further, so that the time related to the performance of the inspection would vary properly with changes in sortie length, the variable g_3 was expressed as follows:

$$g_3 = k_3(a_1 + a_2 + a_3)$$

where k_3 = factor applied to total flying hours,

$(a_1 + a_2 + a_3)$ = total flying hours accumulated each sortie-cycle.

Experience has shown that the requirements for unscheduled maintenance are more closely related to the accomplishment of unscheduled maintenance than to anything else. To reflect this relationship, the variable g_5 was expressed as a function of the variables g_3 and k_4.

$$g_5 = k_5(g_3 + k_4)$$

where k_5 = factor applied to total scheduled maintenance.

When equation (1) was expanded to include the expressions for g_3 and g_5 and appropriate simplifications were made, the following equation resulted:

$$S = (a_1 + a_2 + a_3)(1 + k_3 + k_3k_5) + k_1 + k_2 + k_4 + k_4k_5. \qquad (2)$$

To use equation (2) to determine the number of aircraft, the proportion of the time each aircraft spends on station was defined symbolically as

$$a_2/S,$$

and when the number of aircraft required on station n is given, the total requirement N may be calculated as follows:

$$N = n(S/a_2).$$

However, a more useful expression results when the expanded definition of the sortie-cycle (equation (2)) is used in place of S. Making this change the model for estimating the total number of aircraft required becomes

$$N = (n/a_2)\ [(a_1 + a_2 + a_3)(1 + k_3 + k_3k_5) + k_1 + k_2 + k_4 + k_4k_5]. \quad (3)$$

As will be shown, this relatively simple relationship can provide considerable information about the resource implications of some of the difficult questions raised earlier.

The equation, or model, just described was but one of many that were included in the larger model which was actually used. The requirements for personnel, the cost of purchasing aircraft and missiles, the cost of air base construction, and the cost of supplies and services, are examples of the other items that were treated in similar fashion. A better notion of the comprehensiveness and complexity of the total model can be obtained from viewing the sample output form shown in Appendix A. However, inasmuch as the sensitivity analyses performed with the aircraft model alone illustrate quite well those conducted with the larger model, they have been selected for further discussion here.

Even though the KC-135 had much to recommend it, you will remember that the cost analyst had some reservations which, as it evolved, were based largely on a judgment about the importance of aircraft endurance. Because the number of aircraft required largely determined the system cost, the aircraft model (equation (2)) was used to investigate the relationship between endurance and the number of aircraft. The first step in the analysis was to highlight the desired relationship by restructuring the model slightly. The variable e, representing the aircraft endurance, was substituted for the sum of the terms a_1, a_2, and a_3. However, to maintain the identity of a_2, the time effective on station, the sum of a_1 and a_3 was set equal to the constant K_o, and a_2 became $e - K_o$. Further, as their values would be unaffected by changes in endurance, k_1, k_2 ... k_5 were combined appropriately and represented by constants: K_1 was substituted for the sum of 1, k_3 and k_3k_5; and K_2 was substituted for the sum of k_1, k_2, k_4 and k_4k_5. The equation was then rewritten

$$N = \frac{nK_1e + nK_2}{e - K_o} . \tag{4}$$

It can be seen that K_1 represents the time required to be spent on the ground, that is, dependent on the flying hours, increased by one; K_2 reflects that ground time related only to the accomplishment of a sortie: and K_o is the time spent in the air both going to and returning from the station. One could see from equation (4) that as the endurance e approached the value of K_o, a requirement for an infinite number of aircraft was implied which meant that an aircraft had to have at least enough endurance to go and return from the station. The effect of very long endurance was shown by recasting equation (4) as follows:

$$N = \frac{nK_1e}{e-K_o} + \frac{nK_2}{e-K_o} .$$

It was seen that when e was allowed to become infinitely large, the equation became essentially

$$N = nK_1 .$$

Those activities, K_2, which are related only to the accomplishment of the sortie, become insignificant as the endurance becomes large, and are therefore conveniently assumed to be zero. This says that at least enough aircraft to cover both the on-station requirements (n), and the ground requirements generated by flying hours are necessary. All of this suggests that the number of aircraft required is indeed sensitive to the endurance and that in general the longer the endurance, the fewer the number of aircraft required.

After this preliminary examination, endurances representative of a range of candidate aircraft and the appropriate values for the equation constants were used to solve equation (4) and the results are shown graphically in Fig 3. As was expected, the shorter the endurance, the larger the number of aircraft required. More important, however, the curve implied that for relatively short endurance aircraft, the exact endurance was critical, while the same was not true for longer endurance aircraft. Further, the gains to be achieved by extending endurance decrease rapidly with successive increments of endurance. Indications were that an aircraft with an endurance falling just to the right of the inflection in the curve would be desirable.

To tie these generalities to something more specific, the cost analyst carried out the research that resulted in the information shown in Fig. 4. It was pointed out that endurances representing the KC-135 and other current jet transports were typical of those shown on the lower end of the endurance scale. An indication of the problems associated with obtaining aircraft with more endurance was also provided. It was pointed out that the first, and apparently most valuable, increment of endurance could be achieved by developing and building a new Long Endurance Aircraft (LEA). No state-of-the-art problems were anticipated. Further, the endurance of the LEA could be increased simply by making it larger. However, if still more endurance was sought, a complete research and development program involving novel innovations such as laminar flow control and regenerative engines would be required.

Some of the characteristics of the ground operation that influenced the requirement for aircraft were examined next. First, the implications of scheduling maintenance on a round-the-clock basis rather than an 8-hour day were investigated. Since the calculations made thus far were based on single shift maintenance, the impact of adding a second and third shift can be shown by repeating the calculations with different values assigned to the variables of the equation that reflect the time required to perform maintenance k_3 and k_4. These were doubled and tripled in turn with the results shown in Fig. 5. The essential point of this presentation was that if relatively short endurance aircraft were used, the gains to be achieved by switching to multi-shift

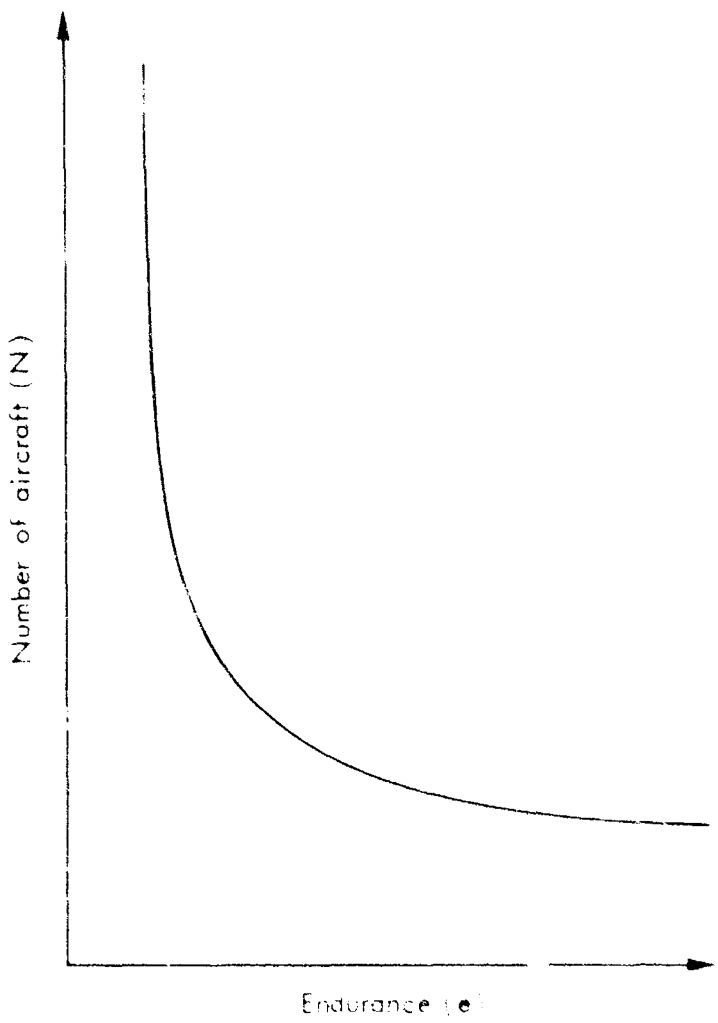

Fig. 3—Number of aircraft versus endurance

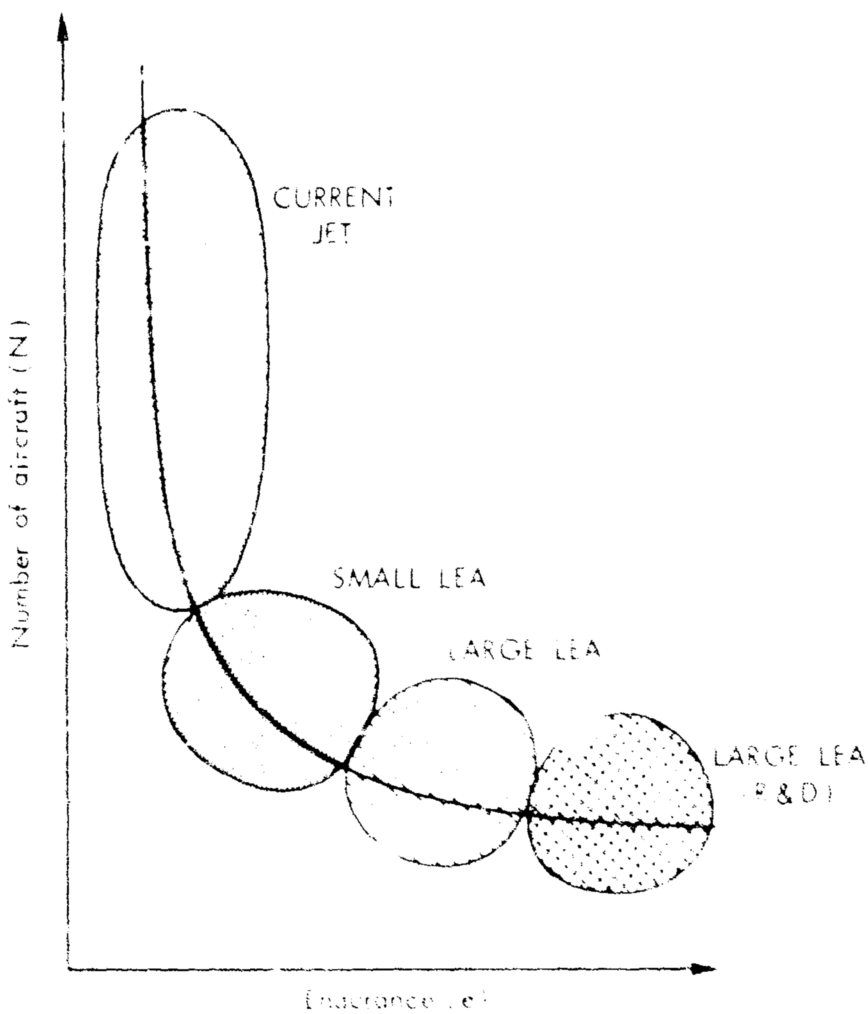

Fig. 4—Number of aircraft versus endurance

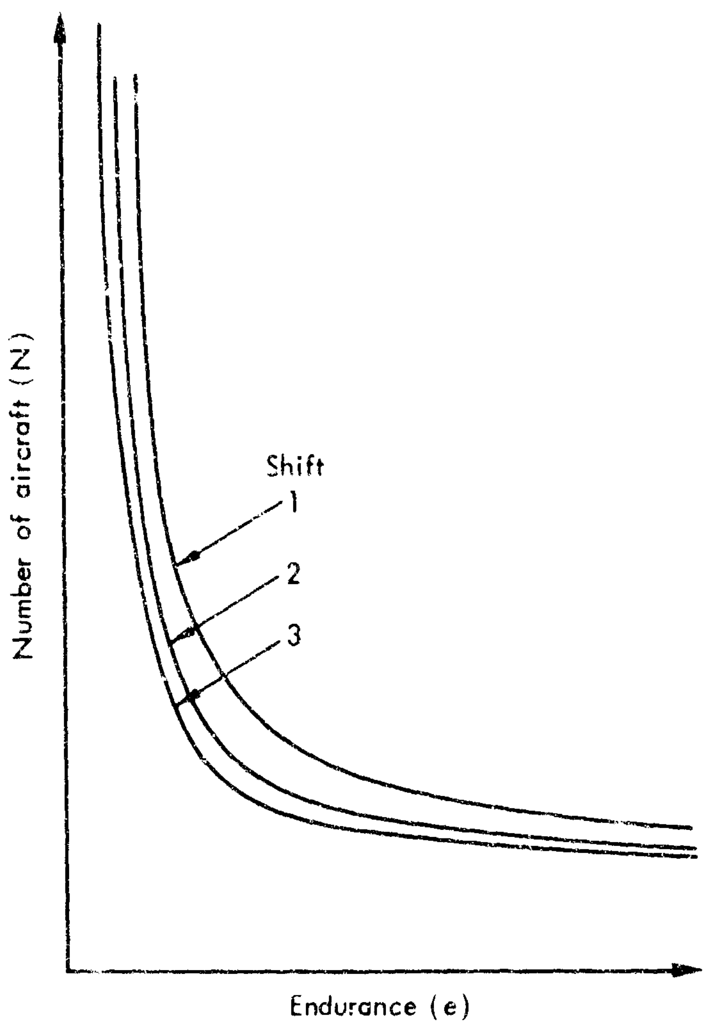

Fig. 5—Number of aircraft versus endurance and number of maintenance shifts

maintenance were significant. On the other hand, as aircraft endurance was increased the gains were decreased. This relationship is illustrated in Fig. 6.

Following this, the amount of time required to on/off-load the aircraft was assumed to be alternately double, and half, the amount assumed thus far, and the results are shown in Fig. 7. The percentage of the fleet effective on station at any time has now been used as the dependent variable, instead of the total number of aircraft. Figure 7 conveys much the same information as did Figs. 5 and 6. When relatively short endurance aircraft are used, any reductions in the amount of time spent on the ground yield significant savings. However, as the endurance of the aircraft becomes larger, the savings to be realized become smaller.

The next stage was to analyze the impact of changes in the time required for an aircraft to make the round trip from base to station, and the results are shown in Fig. 8. These curves are similar to the one shown in Fig. 3; however, it may be noticed that as the round trip time becomes longer, the minimum endurance required becomes greater, which indicates that there may be cases where the minimum endurance required is sufficiently high to eliminate some aircraft from consideration. It once again appears, however, that if an aircraft with long enough endurance is available, the round trip time is of little concern. The time required for the round trip can be viewed as a proxy for a number of other system variables--the off-shore distance, the location of the bases, and the speed of the aircraft. As will be remembered from the earlier discussion, there was considerable uncertainty associated with each of these.

If one were to recapitulate at this point, the conclusion would probably be that the choice of the KC-135 was not a good one. Considerable uncertainty exists with respect to a number of the system parameters and a long endurance aircraft promises to provide substantial insurance against unfavorable outcomes. However, all the indications seem to point to a relatively small long-endurance aircraft. It is important to collect one's thoughts as above, but it is equally important not to be too easily influenced as should become evident.

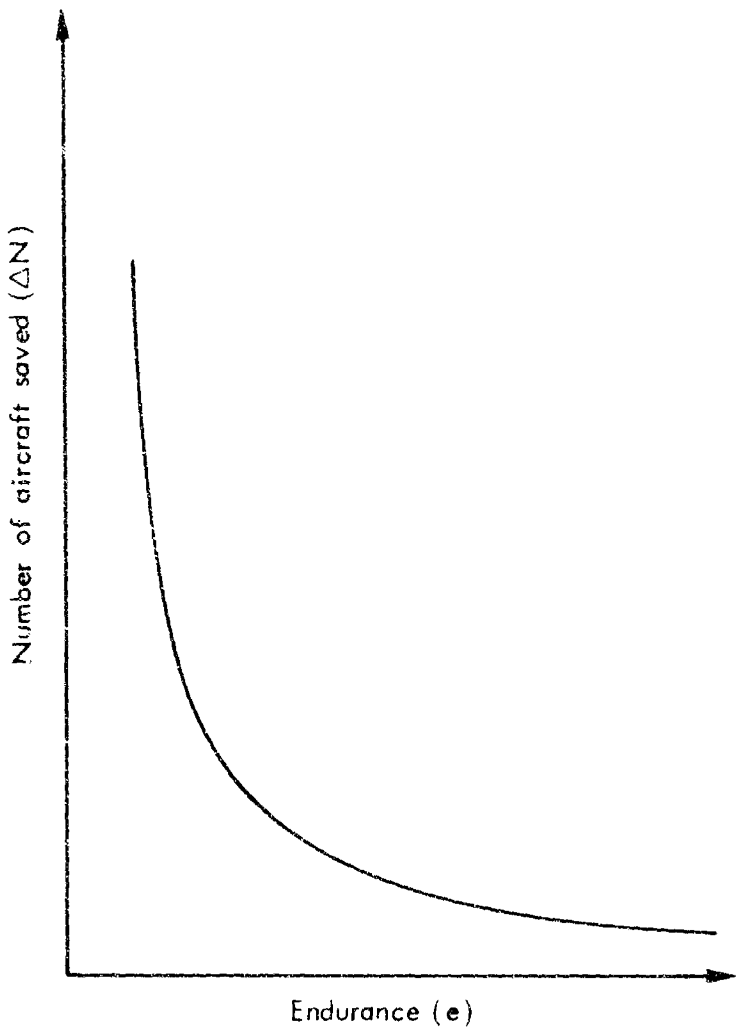

Fig. 6—Aircraft saved by adding 2nd and 3rd shift maintenance versus endurance

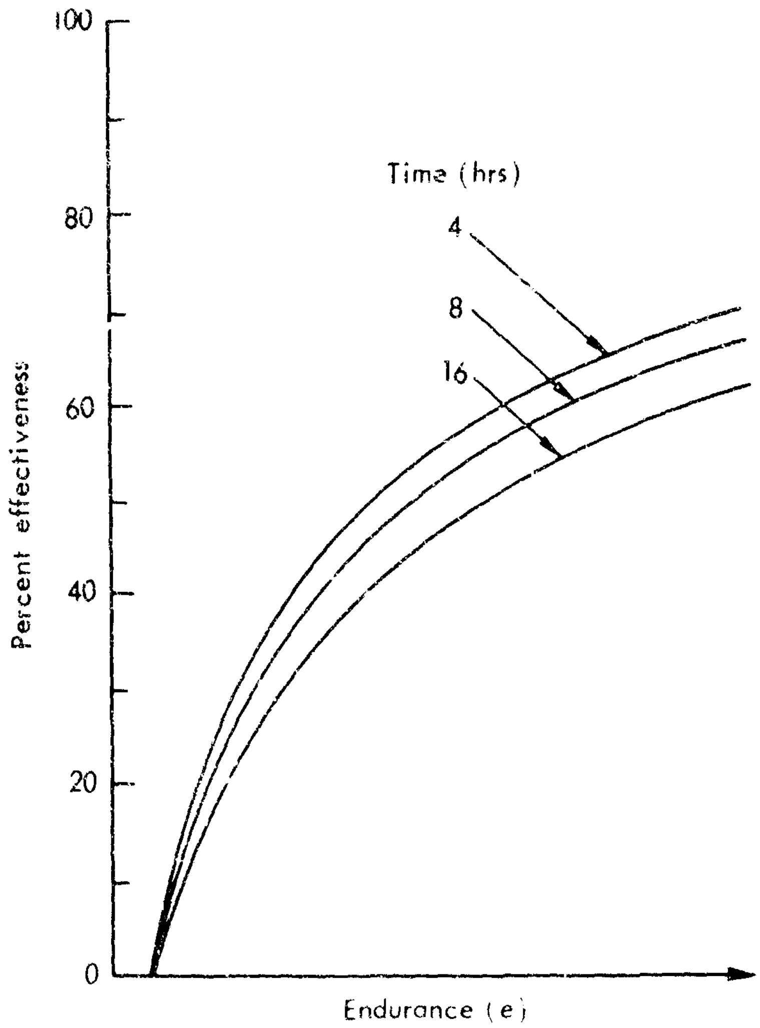

Fig. 7—Percent of aircraft effective on station versus endurance and time to on and off-load aircraft

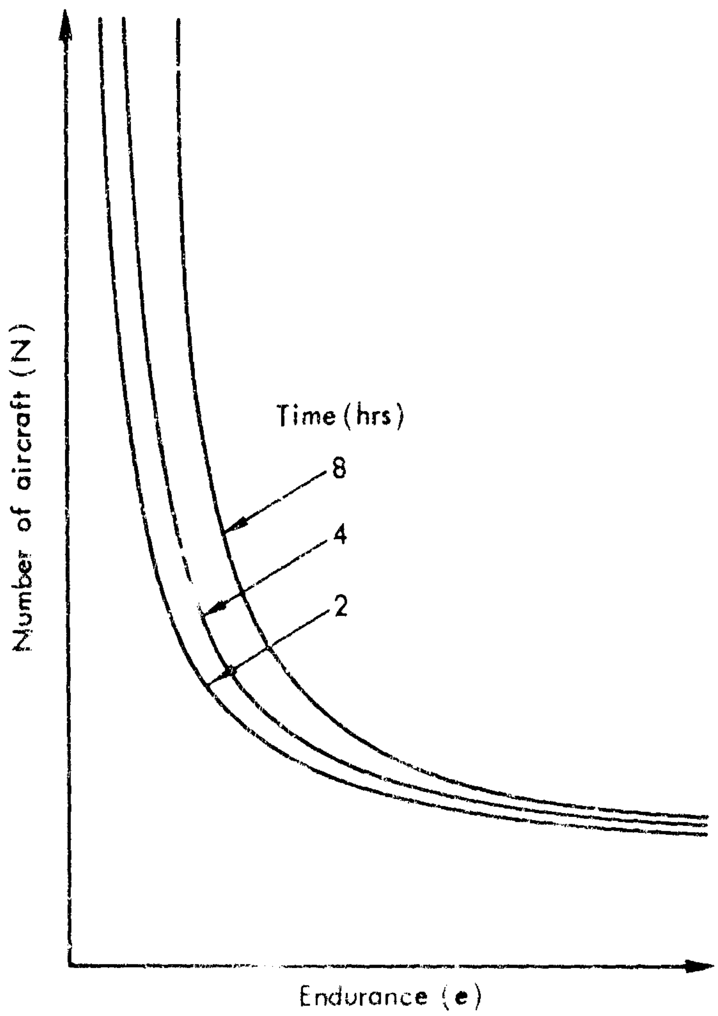

Fig. 8—Number of aircraft versus endurance and time from base to station and back

An area of uncertainty not yet mentioned has to do with enemy tactics. The whole idea of providing uniform coverage of a pre-determined area assumes implicitly that the enemy submarine force will be deployed similarly. No provision has been made to counter a tactic of "wolf-packing" or otherwise saturating a particular section of the defense zone. There were a number of ways suggested for doing this. One was to put more than one aircraft on each station, and another was to provide each aircraft with the capability of handling more than one submarine at a time. The latter seemed the more interesting of the two, but had significant implications regarding the payload requirement for the individual aircraft. These implications are pursued in the following illustration.

It was recognized that there would be some flexibility with respect to the allocation, between fuel and payload, of the weight carried by the aircraft. It was further suspected that the extent of this flexibility was very much related to the particular aircraft selected. To provide some insights into this relationship, it was decided to estimate the cost of keeping one million pounds of payload continuously airborne using aircraft typical of each of four general classes* and allowing for a substitution of fuel for payload and vice versa.

The general form of the result, for a single class of aircraft, can be anticipated. Consider the case where all but a very small part of the allowable weight has been given over to fuel. The endurance would be at a maximum which, as has already been demonstrated, tends to reduce the number of aircraft required. However, as the task stipulated is to maintain one million pounds of payload continuously airborne, and each aircraft carries a small payload, a large number of aircraft are required. It is obvious that allowing more payload per aircraft will reduce the number required. The other extreme where essentially all of the weight is allocated to payload, creates an equally unreasonable alternative. With only a small amount of fuel, the endurance becomes very small, thus requiring many aircraft independent of payload per aircraft. For these reasons, the cost versus payload

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*The four general classes are: Current Jet Aircraft, Small Long-Endurance Aircraft, Large Long-Endurance Aircraft, and Large Long-Endurance Aircraft with R&D.

relationship is typified by a curve reflecting a minimum cost at some middle value for payload and high costs for payloads much above or below that value.

Equation (4) was modified to include the relationship between payload and endurance, and to translate the number of aircraft into a total 5-year system cost. For simplicity's sake, a linear relationship between payload and endurance for a given aircraft was assumed. Also, total system cost was estimated strictly as a function of the number of aircraft required. These relationships and the revised model are shown below.

$$e = \gamma + \varphi p$$

where e = the endurance of an individual aircraft

p = the payload

γ and φ = the equation parameters

and

$$C = R + N(I + 5A)$$

where C = the total system cost

R = research and development cost

I = the investment cost per aircraft

A = the annual cost per aircraft

N = the number of aircraft required.

When the total payload to be maintained airborne was identified as P and the above expressions were combined with the expression for determining the number of aircraft (equation (4)), the model used for this evaluation was

$$C = R + \left[\frac{PK_1 \varphi p + PK_1 \gamma + PK_2}{\varphi p^2 + p(\gamma - K_o)}\right] \cdot [I + 5A], \qquad (5)$$

where $P = n \cdot p$ = total payload on station.

When p was assigned, a range of values peculiar to the particular class of aircraft and the travel time K_o was allowed to very between two and eight hours, the results shown in Fig. 9 were obtained.

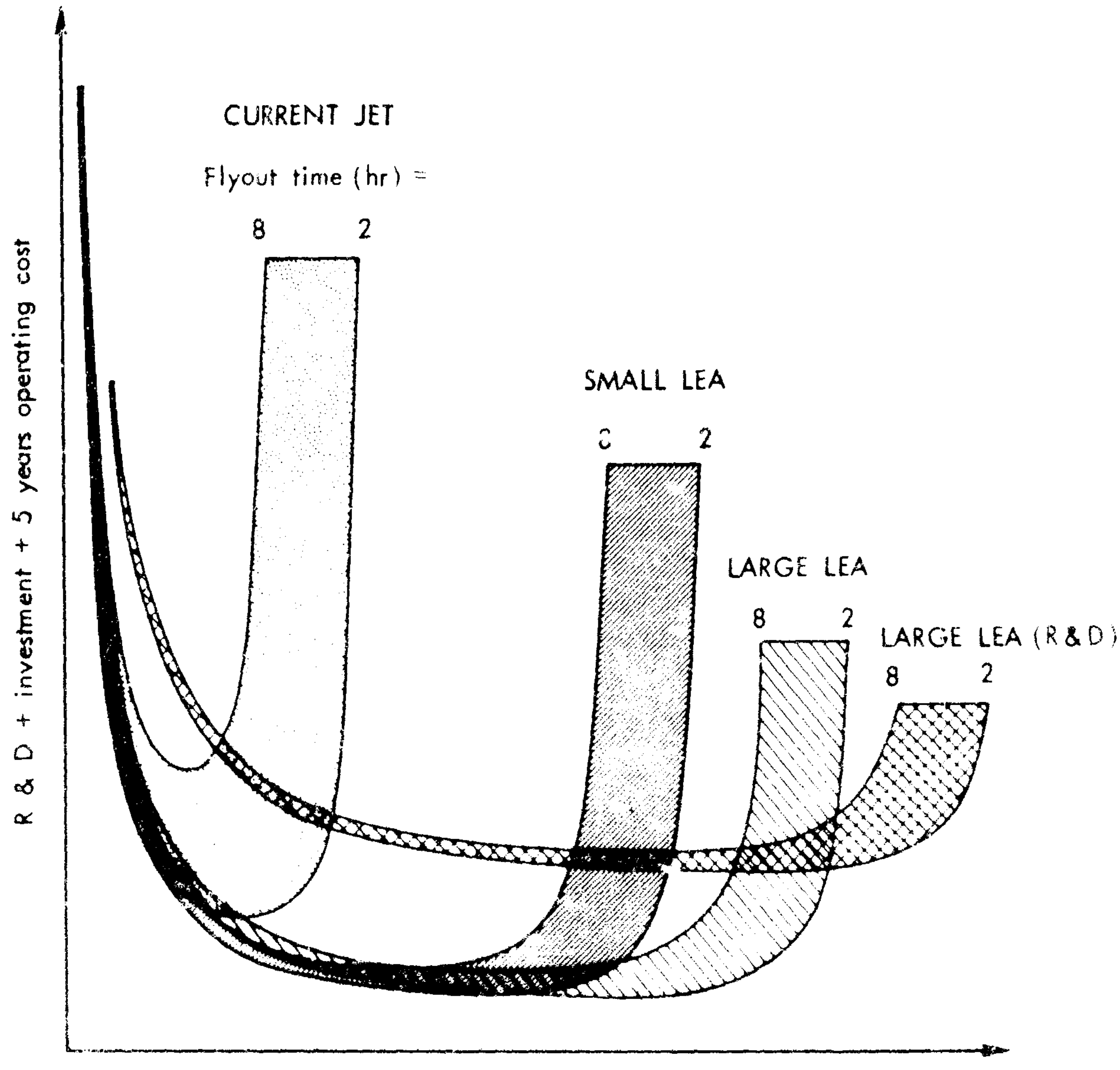

Fig. 9—Total cost of keeping one million pounds of payload on station versus payload weight per aircraft and flyout time

The most striking feature of the curves shown was observed to be the additional loading flexibility achievable with the long-endurance aircraft, for what appeared to be less than the cost of the current jet aircraft. Further, if this flexibility were desirable, going to a larger rather than a smaller long-endurance aircraft was suggested as the differences in cost were slight. These curves further demonstrate the relative sensitivity to travel time exhibited by each of the different types of aircraft.

As the study progressed, more questions about still further features of the system were raised, and each led to more analysis. However, while the subject matter of concern changed, the basic analytical methods used were similar, and detailing them here would not further the objectives of this discussion.

Much of what has been described must appear quite similar to conventional operations research. There are differences, however, and they are significant. Most of these follow directly from the subject matter and the environment of the analysis; the extent to which alternatives can be described and objectives defined. In operations research, it is usual to have relatively well-defined means and objectives, and consequently using appropriate analytical methods optimal solutions can be found. In long-range planning this is seldom the case, and the best that analysis can do is to indicate that, given certain assumptions, one alternative is preferred to another. For long-range planning it is typical that major policy issues are at stake and quantitative analysis provides but one input into the decision process and not always the deciding one. The political and social implications are frequently overriding. For these reasons, resource analysis aims at illuminating issues rather than optimal solutions. One way the two analytical approaches have been described is: Analysis for long-range planning provides the initial filtering of a wide range of ill-defined alternatives, and by so doing identifies those which should become the subjects of more detailed analyses (operations research).

Appendix I

TOTAL SYSTEM COST

SUBMARINE LAUNCHED BALLISTIC MISSILE DEFENSE SYSTEM

CASE NO._____

INITIAL INVESTMENT COSTS

	AIRCRAFT	MISSILE	TOTAL
TOTAL PROCUREMENT			
PRIMARY MISSION EQUIPMENT PRIMARY MISSION EQUIPMENT SPARES			
TOTAL AGE + AEE			
AEROSPACE GROUND EQUIP. AEROSPACE GROUND EQUIP. SPARES AIRBORNE ELECTRONICS EQUIP. AIRBORNE ELECTRONICS EQUIP. SPARES			
TOTAL FACILITIES			
TOTAL TRAINING AND TRAVEL			
TRAINING TRAVEL			
TOTAL OTHER INVESTMENT			
INITIAL STOCKS ORGANIZATIONAL EQUIPMENT TRANSPORTATION			
TOTAL INITIAL INVESTMENT			

Appendix II

ANNUAL OPERATING COSTS

	AIRCRAFT	MISSILE	TOTAL
TOTAL OPERATIONS			
MAINTENANCE			
ATTRITION			
REPLACEMENT			
CONSUMPTION			
TOTAL AGE AND AEE MAINTENANCE			
AEROSPACE GROUND EQUIP. MAINT.			
AIRBORNE ELECTRONICS EQUIP. MAINT.			
TOTAL FACILITIES MAINT. + REPLACE.			
FACILITY MAINTENANCE			
FACILITY REPLACEMENT			
TOTAL PERSONNEL			
PAY AND ALLOWANCES			
TRAINING			
TRAVEL			
TOTAL OTHER OPERATING			
REPLACEMENT OF ORGANIZATIONAL EQUIP.			
TRANSPORTATION			
MISCELLANEOUS			
TOTAL ANNUAL OPERATING			
RESEARCH AND DEVELOPMENT			
TOTAL 5-YEAR SYSTEM COST			

Appendix III

MISCELLANEOUS DATA

CASE NUMBER...
NUMBER OF BASES PER SYSTEM..................................
NUMBER OF STATIONS PER SYSTEM...............................
ENDURANCE HOURS...
RESERVE FLYING HOURS PER FLIGHT.............................
FLYING HOURS FROM BASE TO STATION...........................
OPERATIONAL AIRCRAFT PER SYSTEM.............................
COST OF AIRCRAFT NUMBER 1...................................
CUMULATIVE COST CURVE SLOPE (AIRCRAFT)......................
PROCUREMENT LEVEL FOR AIRCRAFT..............................
MONTHLY FLYING HOURS PER CREW...............................
HOURS IN MAINT. AND SERV. PER MISSION.......................
LAPSED HOURS PER MISSION INCL. MAINT........................
EFFECTIVE UTILIZATION RATE (PERCENT)........................
EFFECTIVE TIME ON STATION (HOURS)...........................
OPERATIONAL AIRCRAFT PER BASE...............................
TOTAL PERSONNEL PER BASE....................................
NUMBER OF SHIFTS PER DAY....................................

NUMBER OF MISSILES PER AIRCRAFT.............................
WEIGHT OF EACH MISSILE......................................
COST OF MISSILE NUMBER 1....................................
CUMULATIVE COST CURVE SLOPE (MISSILE).......................
PROCUREMENT LEVEL FOR MISSILES..............................
OPERATIONAL MISSILES REQ. PER SYSTEM........................

PERSONNEL REQUIREMENTS

	OFFICERS	AIRMEN	MILITARY	CIVILIANS	TOTAL
ADMINISTRATION					
SQUADRON HQ.					
FLIGHT CREW					
MISSILE					
MAINTENANCE					
SUPPORT					
TOTAL					
RATED NON-CREW					